

Low-Metallicity Gas Clouds in a Galaxy Proto-Cluster at Redshift 2.38

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ABSTRACT

We present high resolution spectroscopy of a QSO whose sight-line passes through the halo of a pair of elliptical galaxies at redshift 2.38. This pair of galaxies probably lies at the center of a galaxy proto-cluster, and is embedded in a luminous extended Ly α nebula.

The QSO sight-line intersects two small gas clouds within this halo. These clouds have properties similar to those of high velocity clouds (HVCs) seen in the halo of the Milky Way. The gas is in a cool ($< 2 \times 10^4$ K) and at least 20% neutral phase, with metallicities in the range $-3.0 < [\text{Fe}/\text{H}] < -1.1$ and neutral hydrogen column densities of $\sim 10^{19.5} \text{cm}^{-2}$.

The origin of these clouds is unclear. The presence of low metallicity gas within this possible proto-cluster implies either that the intra-cluster medium has not been enriched with metals at this redshift, or the clouds are embedded within a hot, ionized, metal-rich gas phase.

Subject headings: galaxies: clusters: individual (2142-4420) — galaxies: halos — quasars: absorption lines

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1. Introduction

There has been considerable recent work on investigating the inter-relationship between gas (traced by QSO absorption lines) and galaxies at high redshifts (eg. Pascarelle et al. 2001; Francis et al. 2001; Williger et al. 2002; Adelberger et al. 2003; Zhan, Fang & Burstein 2003). A complex picture is emerging, with gas tracing galaxies on larger scales but some classes of absorption-line system avoiding galaxies on small scales.

QSO absorption-line measurements such as these could potentially shed light on the origin of the highly metal enriched intra-cluster medium of galaxy clusters today. Many models have been proposed (eg. Renzini 1997; Chiosi 2000; Martinelli, Matteucci and Colafrancesco 2000; Aguirre et al. 2001; De Lucia, Kauffmann & White 2003) to produce this gas, but all have problems, and there is currently no consensus.

In this paper, we present high resolution spectra of a QSO that lies behind a probable galaxy proto-cluster at redshift 2.38 (Fig 1). QSO LBQS 2139–4434 lies at redshift 3.23. Its sight line passes only $22''$ (160 projected proper kpc, for $H_0 = 70\text{km s}^{-1}\text{Mpc}^{-1}$, $\Omega_{\text{matter}} = 0.3$ and $\Omega_{\Lambda} = 0.7$) from the extremely red object B1. Francis et al. (2001) demonstrated that B1 is actually a pair of large elliptical galaxies at redshift 2.38..

B1 is embedded within a luminous, extended $\text{Ly}\alpha$ emitting nebula or “blob”. Such $\text{Ly}\alpha$ nebulae are thought to be associated with massive dark halos, and may be the ancestors of cooling flows today (Steidel et al. 2000; Francis et al. 2001). It lies within a probable galaxy proto-cluster (Francis and Hewett 1993; Francis et al. 1996; Francis, Woodgate and Danks 1997; Francis, Wilson and Woodgate 2001), which is itself embedded in a 80 Mpc scale “Great Wall” (Palunas et al. 2004; Francis et al. 2004).

This sight-line thus allows us to probe the gas in an unusual part of the early universe: the halo of an cluster elliptical galaxy.

2. Observations and Reduction

Our existing spectra of LBQS 2139–4434 (Francis and Hewett 1993; Francis, Wilson and Woodgate 2001) were of too low a resolution and narrow a wavelength coverage to seriously constrain the physical properties of the gas. We therefore re-observed it using the University College London Echelle Spectrograph (UCLES) on the Anglo-Australian Telescope (AAT). Observations were carried out on the nights of 2001 August 20 — 23 and the total usable integration time was 30,600 sec. D’Odorico, Petitjean & Cristiani (2002) independently obtained high resolution spectra of this QSO, using the UVES spectrograph. They kindly

allowed us to use their spectrum in this analysis.

The data were reduced using standard procedures, and set to the vacuum heliocentric frame. Absorption-lines properties were measured interactively using the XVOIGT program (Mar and Bailey 1995). We fit our UCLES spectrum, the UVES spectrum, and a lower resolution AAT spectrum which gave better coverage at UV wavelengths (Francis, Wilson and Woodgate 2001), using for each line whichever spectrum gave the most reliable data. Where a given line was seen in multiple spectra, the derived parameters were always consistent within the error bars. Parameters we derived from the UVES spectra agree very well with those derived by D’Odorico, Petitjean & Cristiani (2002).

3. Results

QSO LBQS 2139–4434 was previously known to show high equivalent width Ly α absorption at the redshift of the elliptical galaxies making up B1 (and of the cluster). We confirm this: the absorption centroid redshift matches the C IV emission-line centroid of B1 to within 200km s^{-1} , the uncertainty being dominated by the width of the emission lines.

For the first time, we unequivocally detect metal-line absorption from this absorption-line system (Fig 2). No high ionization absorption is seen: the tentative detection of C IV by Francis, Wilson and Woodgate (2001) turns out, at higher resolution, to be caused by blends of unrelated lines at other redshifts.

The metal-line absorption is clearly resolved into two narrow components, separated in velocity by 59km s^{-1} : a lower redshift component (component 1) at $z = 2.3797$ and a higher redshift component (component 2) at $z = 2.3804$. Both components are narrow and spectrally unresolved: we place upper limits on the Doppler b parameter of $< 6.0\text{km s}^{-1}$ in all transitions. For the Fe II transitions of component 1 we can place a tighter upper limit of $b < 5\text{km s}^{-1}$. There is no evidence for velocity substructure within either of these components.

If we assume that the neutral hydrogen is located in one or both of the metal-line clouds, this allows us to break the degeneracy (noted by Francis, Wilson and Woodgate (2001)) between velocity dispersion and column density in our fits to the Ly α emission profile, and measure the neutral hydrogen column density. The combined neutral atomic hydrogen column density is $10^{19.7 \pm 0.1}\text{cm}^{-2}$. We are unable to constrain how it is divided up between the two components.

There is also a strong degeneracy between the assumed velocity dispersion b and the

inferred metal column densities. For component 1, we can place a lower limit of $b > 2\text{km s}^{-1}$ from the O I line: if b were lower, then to get a good fit we would need such a high column density that we would start to see damping wings, which are not observed. We cannot place an observational lower limit on b in component 2, but physically the sound speed of even a cold neutral medium should be at least 1km s^{-1} , so we take that as our lower limit. In Table 1, we use these limits on b to bracket the possible column densities.

We list upper limits on non-detected lines by assuming the same limiting values of b , and seeing interactively how strong such an absorber could be before the residuals go clearly into emission.

4. The Physical State of the Absorbing Gas

The strength of the low ionization species, such as O I and Si II, compared with our upper limits on high ionization species such as C IV and Si IV clearly indicate that the absorbing gas is cool, and at least partially neutral.

There are two possibilities for the temperature of these gas clouds: we could have a warm neutral/partially ionised phase with $T \sim 10^4\text{K}$ or a cold neutral phase with $10^2 < T < 10^3$ K (eg. Sutherland & Dopita 1993).

We modeled the first possibility (warm neutral/partially ionised phase) using Gary Ferland’s CLOUDY code (Ferland 1996). For plausible choices of the UV ionizing background (Haardt & Madau 1996; Scott et al. 2000), we can reproduce the absorption-line columns measured with a cloud of density $0.1 < N_H < 10\text{cm}^{-3}$, size 2 — 200 pc and mass $0.001 - 10 M_\odot$. If the density is towards the lower end of this range, the hydrogen could be up to $\sim 80\%$ ionised.

The second possibility is almost impossible to model, due to the complex molecular cooling processes, but cold neutral gas in our own galaxy does show ionization states and column densities comparable to those we observe.

Which of these models is correct? Our stringent upper limits on the velocity dispersions of the two components provide some evidence in favor of the cold model. The sound speed in the warm model is $\sim 10\text{km s}^{-1}$, while in the cold model it would be only $1 - 3 \text{ km s}^{-1}$. One would expect the internal turbulent velocity dispersions to be comparable to the sound speed. The rapid movement of these clouds through B1’s dark matter halo should be ample to excite and sustain such turbulent motions. Our upper limit of $B < 6\text{km s}^{-1}$ is thus most consistent with a cool model.

On the other hand, if the velocity dispersion really is low ($b \sim 2 \text{ km s}^{-1}$), we are forced to invoke extremely large O I column densities to fit the observed absorption line. This would imply an extraordinary overabundance of oxygen compared to silicon: $[\text{O}/\text{Si}] > 1.5$ for $b \sim 2$. Larger values of b bring the inferred column density of O I down to more reasonable values. A cold neutral phase with supersonic turbulence would be an interesting possibility.

If the gas were in the cold phase, we might expect dust to be present. We can place upper limits on the quantity of dust by noting, however, that the QSO has a UV continuum slope indistinguishable from other QSOs in the Large Bright QSO Sample (Francis et al. 1991). This allows us to place a rough upper limit on the extinction in these clouds of $E(B - V) < 0.1$.

We also note (Fig 2) that the O I line touches zero flux. Thus the absorbing cloud must be large enough to completely obscure the background QSO continuum emitting region.

In conclusion, we are unable to discriminate between the two physical models. We consider the oxygen overabundance argument somewhat stronger than the velocity dispersion argument, but neither is conclusive. Higher resolution spectra will be needed to resolve this puzzle.

5. Conclusions

Our line of sight through the halo of B1, and probably through the central regions of a galaxy proto-cluster, is thus intersecting two small gas clouds. Their properties are very similar to those of high velocity clouds (HVCs) in the halos of our own galaxy (eg. Gibson et al. 2001; Tripp et al. 2003). Their metallicities must be low: $-3.0 < [\text{Fe}/\text{H}] < -1.1$, $[\text{C}/\text{H}] < -1.65$ and $-2.9 < [\text{Si}/\text{H}] < -1.65$ (Table 1, and allowing for neutral hydrogen fractions as low as 20%). The warmer the gas, the lower our inferred metallicity. If there is substantial molecular hydrogen, the metallicities would be lower still.

Given the continued controversy over the nature even of the HVCs in our own galactic halo, it would be foolhardy to make dogmatic statements about the origins of these distant clouds. Many of the same models that have been proposed for our local HVCs (eg. tidally disrupted dwarf galaxies, in-falling primordial gas, gas trapped in dark matter sub-halos, debris from galactic fountains) could apply here.

The metallicities we measure for these clouds are lower than the typical intra-cluster medium (ICM) metallicities of galaxy clusters today. This implies either that this enrichment of this cluster had not yet taken place, or that the cold gas clouds we see are in some way

isolated from the enriched gas. It is possible, for example, that these clouds are embedded in a very hot, ionized, X-ray emitting, metal-rich ICM. We would not detect such a hot phase in absorption. We do not detect B1 in X-rays (Williger et al. 2004, in preparation), but our current limits do not place tight constraints on the existence of such an ICM.

These observations may also shed light on the enigmatic Ly α blobs. While our sight-line does not pass through the blob, it does probe the same dark matter halo. It is quite possible that the Ly α emission region is made up of small clouds similar to those we are probing in absorption. The emission could be driven by photoionization and photo-evaporation of these clouds by some concealed AGN, or could be produced by fast shocks created at cloud-cloud collisions, as discussed by Francis et al. (2001).

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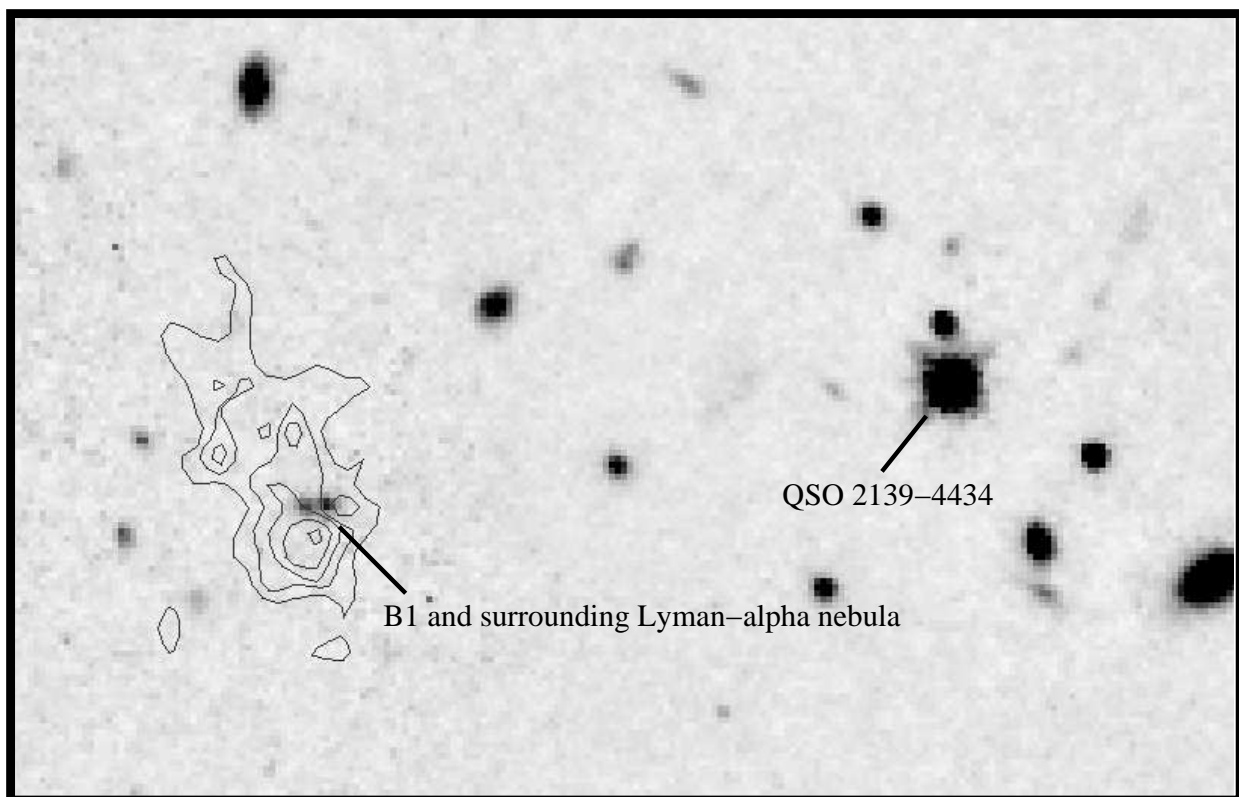


Fig. 1.— Close-up image of QSO 2139–4434, and the $z = 2.38$ galaxy B1, which lies $22''$ away. Greyscale is a NICMOS F160W image (rest-frame B -band), while the contours show $\text{Ly}\alpha$ emission, measured with the Rutgers Fabry-Perot on the CTIO Blanco Telescope.

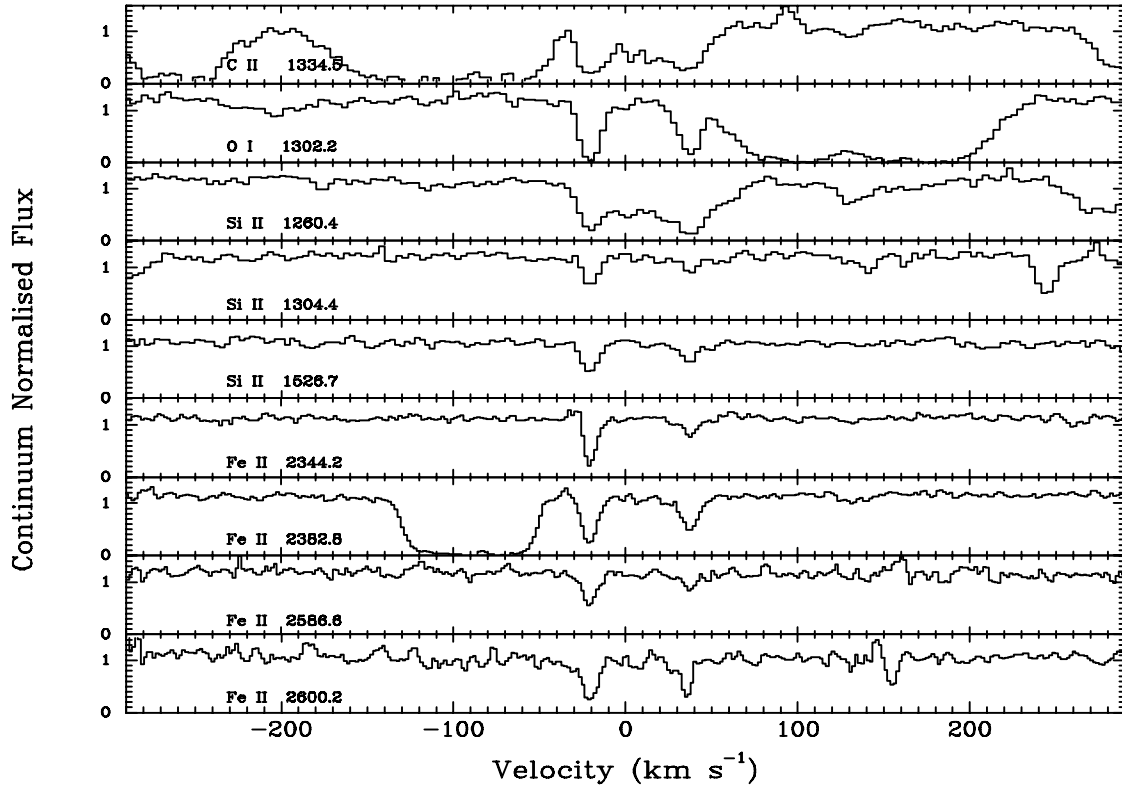


Fig. 2.— UVES spectra of the nine best metal-line detections in QSO 2139-4434. Velocities are relative to a nominal redshift of 2.38.

Table 1. LBQS 2139–4434 Absorption-Line Column Densities

Ion	Log(Column Density) (cm^{-2})			
	z=2.3797 Component		z=2.3804 Component	
	$b = 2\text{km s}^{-1}$	$b = 5\text{km s}^{-1}$	$b = 1\text{km s}^{-1}$	$b = 6\text{km s}^{-1}$
H I	19.6 — 19.8			
C I	<12.2	<12.2	<12.8	<12.8
C II	<14.5	<15.5	<14.4	<13.9
C IV	<12.4	<12.5	<12.5	<12.5
O I	16.4 — 17.0	14.2 — 14.7	16.9 — 17.3	14.0 — 14.3
Si I	<11.7	<11.9	<11.6	<11.9
Si II	13.0 — 13.3	13.0 — 13.1	12.4 — 13.1	12.5 — 12.9
Si IV	<11.6	<11.8	<12.2	<12.4
S I	<12.0	<11.9	<12.4	<12.6
Fe II	13.8 — 13.9	13.0 — 13.1	13.0 — 13.2	12.6 — 12.8